Study on the Eccentricity Distribution of the Initial Condition for Uranium-Uranium Collisions

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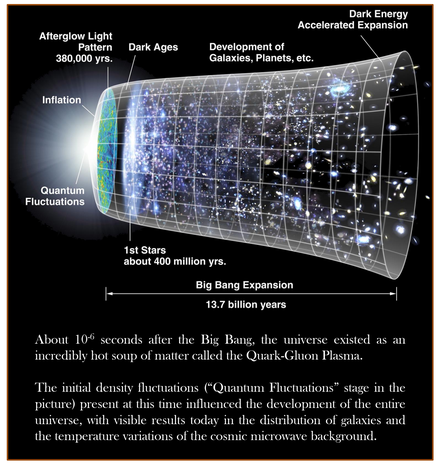
Background

- The **Quark-Gluon Plasma (QGP)** is a state of matter in which the quarks that make up familiar protons and neutrons, together with the strong force carrying gluons, exist as a deconfined, free flowing liquid.
- At the **Relativistic Heavy Ion Collider** (RHIC) in New York, nuclei are collided at high energies to generate QGP in little fireballs whose temperatures exceed 4 trillion degrees Fahrenheit.
- Analogous to the Standard Model for the Big Bang, we are working to establish a **Standard Model for the Little Bang** which models the behavior of the QGP generated in these collisions.

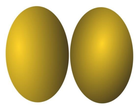


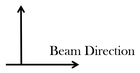
About 10^{-6} seconds after the Big Bang, the universe existed as an incredibly hot soup of matter called the Quark-Gluon Plasma.

The initial density fluctuations ("Quantum Fluctuations" stage in the picture) present at this time influenced the development of the entire universe, with visible results today in the distribution of galaxies and the temperature variations of the cosmic microwave background.

Uranium-Uranium Collisions

Side – Side





Tip-Tip

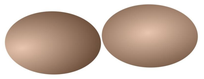
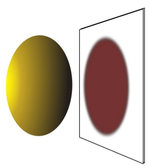


Figure A: Unlike the spherically shaped lead or gold nuclei traditionally used at RHIC, uranium nuclei are elliptically deformed and thus look more like a football. The result is that orientation matters when we study the resulting collisions. Above are the two extremes for the possible collision types, side-side and tip-tip events.



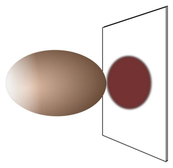
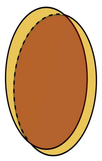
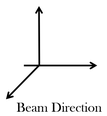


Figure B: At relativistic speeds, the nuclei are Lorentz contracted so that we are essentially colliding two pancakes as opposed to two footballs.





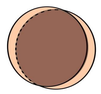


Figure C: The initial conditions for the QGP are influenced by two main factors:

1. The overlap area of the collision profile, which is a function of the geometry of the nucleus and the centrality of the collision (numerically, the "impact parameter").
2. The quantum fluctuations determining the distribution of protons and neutrons in the nucleus, and their resulting participation (as this is the stuff actually colliding).

We see here that the overlap area varies significantly between the two extreme collisions types. The side-side collision is more elliptic than the tip-tip collision.

Problem: "The Knee"

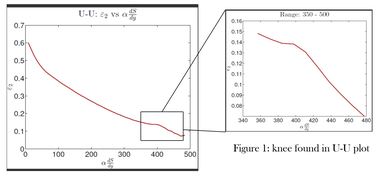


Figure 1: knee found in U-U plot

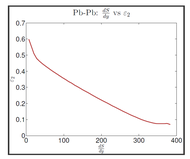


Figure 2: the usual Pb-Pb plot

Here we have plotted up to an unknown proportionality constant α the integrated entropy density $\frac{dS}{dy}$ versus the ellipticity ϵ_2 of the initial collision profile, for many simulated U-U collision events. Intuitively, the quantity $\frac{dS}{dy}$ is related to the number of nucleons that participate in the collision.

Figure 2 represents the results expected from collisions with spherical nuclei. Figure 1 is the U-U result, which we notice has a new knee feature at approximately $\alpha\frac{dS}{dy} = 400$. This can be understood if we look more closely at the elliptic deformation of the uranium nuclei.

Overlap Area

- Since overlap area is one of the two major factors influencing the initial profile, we consider how it behaves plotted over $\alpha\frac{dS}{dy}$.
- Note that the overlap area begins to decrease immediately after reaching the knee.
- If we refer back to Figure C, we note that the overlap area in central collisions is smaller for tip-tip events as opposed to side-side events.
- Impact parameter decreases as we move to higher $\frac{dS}{dy}$, so the events in the region of interest are approximately central collisions.
- Therefore, since the overlap area is decreasing and the events are central, we suggest there are more tip-tip events at higher values of $\frac{dS}{dy}$.

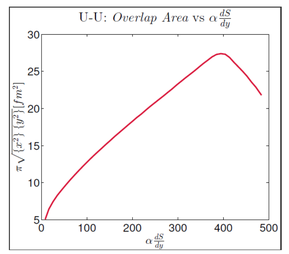


Figure 3: The overlap area is a measure of the portion of collision area shared by the profiles of the two nuclei.

Orientation

- To confirm that a bias toward tip-tip events relates directly with the knee feature, we first output the initial angular position of the uranium nuclei from the code, and then count up the types of orientation in our desired range of $\alpha\frac{dS}{dy}$.
- In the plot, tip-tip events correspond to angles 0 or π, thus $\cos\theta$ values of 1 or -1, while side-side events occur at $\theta = \frac{\pi}{2}$, or when $\cos\theta = 0$.
- Hence, tip-tip events are significantly more frequent than side-side events for collisions in our knee region.

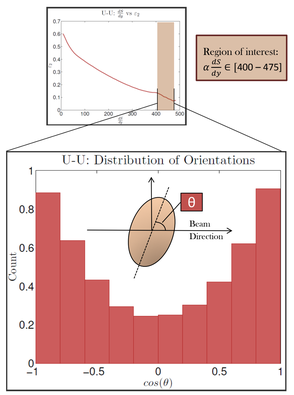


Figure 4: Normalized histogram of orientation angle

Conclusion

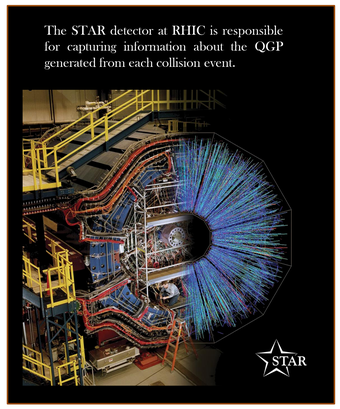
- There are many more nuclei participating per unit area when the two football shaped nuclei collide tip-tip as opposed to side-side, leading to a preferential selection of tip-tip collisions at high $\frac{dS}{dy}$.

Armed with this information about the type of events located in the knee region, we can move to answer why this results in the knee shape:

- Referring back to Figure B, we see that the tip-tip collisions have essentially circular profiles when Lorentz contracted. Clear from Figure C was that this resulted in a collision profile that was not very elliptic, especially when compared to the side-side events.
- The fact that tip-tip events become more likely at high $\frac{dS}{dy}$ tells us that we should expect a resulting decrease in the ellipticity of the collision profile—a consequence we see as the knee in our data.

Future Study

- One interesting property of the QGP is that its behavior is very close to that of an ideal fluid with very small viscosity, or friction resisting the flow.
- As a result, we can use relativistic hydrodynamics to model the evolution of the fireball from the initial condition profiles generated by the collision simulations, giving theorists a way to compare their models to experimental results.
- Currently I am using this code to generate the outputs for my collision data, to compare to data gathered at the STAR detector at RHIC which was presented at the 2012 Quark Matter Conference.
- Next I will be studying the influence of quantum fluctuations on the initial conditions for U-U collisions, and looking at the influence of the shear and bulk viscosity on the hydrodynamic evolution of these events, so that we may continue to work toward a Standard Model for the Little Bang.



References and Thanks

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For reference:
Moreland, Qiu, Heinz, *"A Monte Carlo Program for Fluctuating Glauber and Color-Glass Condensate Initial Conditions"*, (2012)

Image sources:
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